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Modeling for deployment of digital technologies in the cold chain

Vishal Kumar Gupta*. Atanu Chaudhuri**
Manoj Kumar Tiwari*

** Department of Industrial & Systems Engineering, Indian Institute of Technology Kharagpur, Kharagpur, India, (e-mail: vkg03@hotmail.com).*
*** Department of Materials and Production, Aalborg University, A.C. Meyers Vænge 15, Copenhagen 2450 Denmark; (e-mail: atanu@mp.aau.dk, atanu@business.aau.dk)*
**** Department of Industrial & Systems Engineering, Indian Institute of Technology Kharagpur, Kharagpur, India, (Tel: +91 (3222) 283746; e-mail: mkt09@hotmail.com)*

Abstract: In this paper, we have evaluated the scope of deploying digital technologies like IoT to improve the performance of the cold supply chain. A scenario has been considered where the retailer source fresh produce from the supplier and has outsourced its logistics operations to a third party logistics provider (3PL). 3PL's service level affects the sellable quality and quantity of the produce; however, to improve its service level, the 3PL has to incur additional cost on freshness keeping effort. The retailer can decide the quantity to be sourced from the supplier and whether to employ digital technologies like IoT or not. Moreover, both 3PL and retailer being independent entities, it has been assumed that the retailer has no direct control over freshness keeping effort provided by 3PL. We have examined the case in a newsvendor problem setting, where the freshness of the product influences its randomly distributed demand. In this paper, it has been proved that incorporating IoT can immediately improve the cold chain profits. Our analysis asserts the channel power that large retailers like Walmart enjoy, and outlines the scope for coordination and cooperation in the presence of IoT.

Keywords: Internet of Things, Cold Supply Chain, Fresh Produce, Newsvendor Problem, Industry 4.0.

1. INTRODUCTION

The demand for products, like fresh fruits, flowers, seafood, etc. depends heavily on their freshness level at the point of sale. Therefore, to maintain the freshness, these products are constantly kept in the artificially controlled (mostly chilled) environment. However, fresh produce involves long-distance transportation and often needs multiple modes of transportation. The total loss in quality and quantity that survives to the point of delivery depends on the service level of the logistics provider. However, it is common not to have refrigerated vehicles particularly in developing countries like India and China. According to a report by the National Centre for Cold-chain Development, India has approximately 9,000 reefer vehicles while there is a need to have more than 61,000 reefer vehicles (NCCD, 2015). In comparison, it is reported that France has about 1,40,000 reefer vehicles. Clearly, there is a need to promote cold chain services in countries like India.

It is a topic of interest in the research community to find effective ways to reduce food wastage, and technologies like RFID and Internet of Things (IoT) has given a lot of scope for improvement. There is an increase in research considering the prospect of implementing digital technologies like IoT in the supply chain. However, from the literature, it is evident that cold chain has not got sufficient attention from the research community especially when it comes to prospects of implementation IoT based technologies. In this article, we attempt to present a case where we demonstrate that IoT can really increase the cold chain profit even in the absence of any effort from third-party logistics (3PL) provider to improve its service level. We further find that the total cold chain profit can substantially increase if 3PL improves its freshness keeping effort. Our analysis could be used to design innovative contracts to coordinate so that the retailer and 3PL provider achieves a win-win outcome.

Rest of the paper is ordered as follows. In section 2, literature dealing with applications of IoT in the supply chain is presented, and the literature gap is identified with respect to the cold supply chain. Section 3 presents the problem description based on the research gap identified in the previous section. Next, in section 4, mathematical models are presented where we have formulated profit functions for retailer, 3PL provider, and supplier considering normally distributed demand in a newsvendor setting. In section 5, the numerical experiment and the results are presented. Section 6 concludes this paper while highlighting some of the future scopes.

2. LITERATURE REVIEW

In this section, we have reviewed articles dealing with the benefits and applications of IoT in the supply chain in general. Some of the benefits of IoT in the food supply chain could be

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extended from the article by Pang et al. (2015), where authors pointed out that IoT could enable shelf life prediction, sales premium, precision in food production, reduction of insurance cost, apart from traceability and income-centric value created by it. As mentioned by Ben-Daya et al. (2017), IoT sensors enable efficient collection of data, that could be analyzed and tuned to provide useful information, providing real-time visibility into all aspects of supply chain. This enables early warning systems and to take corrective actions to avoid losses. Moreover, IoT reduces the time between data capture and decision making, enabling a level of agility and responsiveness that has not been observed in the past. IoT also enables management of supply chain operations from remote locations and therefore better coordination with supply chain partners. Zhu et al. (2018) pointed out that, IoT has the potential to enable real-time transfer of signals from consumers to growers and back along the value chain. In fact, data collected thought IoT devices could ultimately empower retailers to control their inventory to cut down wastage. Moreover, real-time data enable retailers to determine when and where customers want a product. Lee et al. 2018 proposed IoT based warehouse management system that employs data analytics and computational intelligence to improve order picking, productivity, and overall logistics.

As concluded in the review articles by Ben-Daya et al. (2017) that even though there is huge interest in IoT among the researchers, applications that address supply chain challenges are still in their early stage, particularly in the domain of food supply chain where one-third of the food produced gets wasted worldwide. Motivated by this, we focused our attention on characteristics of cold chain that sets it apart from the supply chain in general. In the §2.1, peculiarities of the cold chain, particularly the idea of obsolescence and deterioration is discussed. §2.2 presents articles that analytically or numerically approached the problem of IoT in the cold chain. The section focused specifically on literature related to rerouting. Based on literature dealing with the use of IoT in the cold chain, the literature gap is identified and presented in §2.3. At the end of this section, we have listed out some of the contributions this article attempts to make.

2.1 Unique characteristics of cold chain

Fresh products deteriorate in transit and can lose its freshness as time passes. In fact, such a product faces both obsolescence and deterioration. In their pioneering paper, Cai et al. (2010) considered both obsolescence and deterioration probably for the first time, where the quantity of the item that survives at the point of delivery decreased stochastically with time. Authors emphasized the effect of freshness keeping the effort on supply and demand of such items. Authors extended the work in Cai et al. (2013) to come up with optimal decisions for 3PL provider, producer, and distributor. They proposed suitable contracts for better coordination in the given case. Wu et al. (2015) proposed coordinating contracts where distributors outsourced logistics operations to 3PL, whose logistics service quality influenced the sellable quantity and quality. Yu and Xiao (2017) investigated the impact of channel leadership on cold chain service level, pricing decisions and to examine the impact on channel profits. Although there is a number of articles dealing with quality and quantity losses in cold supply chain, IoT based real-time monitoring has not been formulated in a game theoretic setting.

2.2 IoT in cold chain

IoT can be an enabling technology to assess both obsolescence and deterioration in fresh products. In fact, there are several types of sensors that enable real-time assessment of the quality of the product being transported, for example, Biosensors, Integrity Indicators, Time Temperature Indicator, Humidity, Oxygen, Carbon Indicators, and so on (Bibi et al., 2017).

The articles those successfully integrated IoT based technologies into the food supply chain includes that of, Haass et al. (2015) that considered the case of rerouting based on intelligent containers carrying banana being imported to Europe. Authors carried out a simulation study and concluded that intelligent containers packed with sensors could enable its rerouting based on remaining shelf-life. Ruan and Shi (2016) talked about monitoring and assessment of freshness of the product in online demand fulfilments. The authors developed a framework based on IoT technologies to monitor deliveries of fruits. Bogataj et al. (2017) stressed upon the importance of real-time detection of changes in freshness and remaining shelf life of agricultural products while it gets transported. They proposed dynamic rerouting based on the net present value that depends on remaining shelf life at the point of delivery. Mejjaouli and Babiceanu (2018) proposed decision support enabled by RFID devices; two types of decision are considered, first, to stop the transportation of the product or to reroute it closer location depending on its present monitored quality. They proposed the decision to be made by cloud-based temporary virtual machines linked with each and every shipment.

2.3 Gaps from the literature

As already mentioned in the first paragraph of §2.2, IoT devices could be classified into ones that enables environment control and ones those enables the monitoring of the quality of the product. While the first set of sensors helps in freshness keeping effort by timely notifying if anomalies are identified, the other set of sensors helps identify the batches or packets that need to be rerouted to a local market. In other words, technology is already available that could easily monitor quality and quantity losses while the product is being transported. However, to the best of our knowledge, there is no paper that mathematically studied the benefits of implementing IoT in the cold chain while considering the service level provided by 3PL.

Contributions: We propose that there are enough opportunities for implementation of IoT in obsolescence and deterioration detection. However, there is a need to come up with novel coordinating contracts between the parties involved in the cold supply chain to share the benefits extracted from IoT.

Although articles listed in §2.2 dealt with IoT based rerouting and proved it to be beneficial for the supply chain, these articles failed to answer some important question, and those are, how to optimally determine the quantity to be ordered, and how to coordinate with the 3PL in the absence/presence of freshness keeping effort provided by them. This paper studied various such cases in newsvendor setting and presented novel mathematical models that could easily be used to calculate order quantities and profits in real life scenarios. These mathematical models could eventually enable stakeholders to come up with innovative contracts to coordinate.

3. PROBLEM DESCRIPTION

We propose a case of the cold supply chain where there is a retailer, a supplier, and a 3PL provider, assuming that the retailer procures fresh produce from the supplier and outsources its logistics operations to a 3PL provider. To incorporate quantity and quality losses, 'degree of spoilage' and 'degree of freshness' are formulated (see section 4). It is also considered that the wholesale and retail price of the product is fixed and determined by the market forces.

We have considered two cases for the retailer, first, when it employs IoT devices to enable pallet and packaging level monitoring, and second, when it does not employ any IoT. Furthermore, two different cases for the 3PL provider is considered, first when it does not provide freshness control (i.e., zero freshness keeping effort) and when it does invest in freshness keeping effort. For the sake of simplicity, it is assumed that the 3PL provider charges fixed transportation and rerouting cost per unit of the product.

With the help of IoT devices, the retailer can know the condition of the product being transported in real-time. As we have already mentioned in §2.2, the articles those dealt with IoT emphasized upon rerouting of the produce while it is being transported, for example, see Bogataj et al. (2017) and Mejjaouli and Babiceanu (2018). In fact, the use of IoT enables timely rerouting before the product gets to the point that it becomes a complete waste. Taking the cue from these articles, this paper considers that the retailer could reroute the product to a local market while it is monitoring the condition of the product from a control location. If it decides to reroute a deteriorating package, it has to incur an additional cost of rerouting payable to the 3PL provider. However, by doing so, it could salvage the deteriorating product that otherwise would get spoiled by the time it reaches its designated outlet. If not rerouted on the way, the retailer has to incur an additional cost to dispose-off the spoiled products once it gets delivered at the store. For further clarification, a schematic diagram of the problem is presented in Fig. 1.

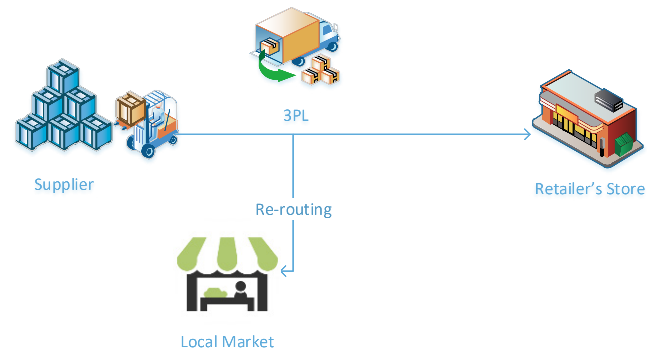

Fig. 1: Schematic diagram of rerouting in Cold Chain enabled by IoT

It is assumed that IoT sensors are implemented at the package level and therefore, to implement IoT, the retailer has to incur a) fixed setup cost on data processing servers, control room, system software, database, etc. and b) cost for implementing sensors on every packet. We have assumed that products being transported are packed into intelligent packages (Janjarasskul & Suppakul, 2018) and are capable of transmitting data to the central control. The fixed setup cost has not been used in the mathematical model as one could easily find the monetary benefit the IoT setup is going to generate per trip, based on the expected life of the setup and expected number of trips possible during that time, one could easily calculate the net present value of the setup.

4. MATHEMATICAL MODEL

The basic approach in papers cited in section 2.1 can be boiled down to freshness keeping effort (τ), surviving function and freshness function. Cai et al. (2010) suggested freshness keeping cost (c) as a function of freshness keeping effort and suggested $c = c_o \tau^k$, where $c_o > 0$, $\tau > 0$ and $k > 1$ such that $c \in [0, \infty)$. So if there is no freshness keeping effort, the freshness keeping cost becomes zero. Furthermore, with slight adaptation from author's proposed model, we propose two terms to represent obsolescence and deterioration. We propose "Degree of spoilage," i.e., ϕ to represent obsolescence at the point of delivery, and "Degree of freshness," i.e., θ to represent deterioration. Both θ and ϕ varies from zero to one, where $\theta = 0$ represents no freshness and $\phi = 0$ means no spoilage. We have assumed the following functions for Degree of spoilage.

$$\phi = \frac{b}{a^{\tau}} \quad , \tag{1}$$

where, $\phi \in [0,1]$, $a \in (1,\infty)$ and $b \in (0,1)$. If a graph of ϕ vs. τ is drawn, the degree of spoilage will decrease with increase in τ and become asymptotic to zero as τ increases further. Similarly, Degree of freshness is assumed to follow (2).

$$\theta = 1 - \frac{\beta}{\alpha^{\tau}} \ , \qquad (2)$$

where, $\theta \in [0,1]$, $\alpha \in (1,\infty)$ and $\beta \in (0,1)$. Once again if the graph of θ vs. τ is drawn, the degree of freshness at the point of delivery will increase with τ and become asymptotic to one as τ increases further.

For the newsvendor setting, it is assumed that the demand is normally distributed and its mean depends on the degree of freshness at the point of delivery, i.e. $\mu = g(\theta)$. In other words, when the product reaches the retailer's store, its demand will be stochastically determined by its freshness level. In this paper, we have assumed the demand follows (3) where, $\mu = \gamma\theta$ and $\gamma > 0$.

$$f(x,\theta) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2} \right) \qquad (3)$$

4.1 Notations, Sets, and Indices

Symbol	*Description*
C_t	*per unit 3PL logistics charges*
c_t	*per unit cost incurred to 3PL partner*
C_r	*per unit extra rerouting charged by 3PL*
c_r	*per unit extra rerouting cost incurred to 3PL*
C_s	*per unit cost incurred to the supplier*
C_{iot}	*cost of IoT implementation per unit quantity dispatched*
W	*the wholesale price charged by the supplier*
S	*per unit cost for disposing of the spoiled products*
O	*Overage cost*
U	*Underage cost*
$F(Q_s)$	*cumulative distribution function for demand*
$f(x,\theta)$	*demand distribution function*
σ	*standard deviation of normally distributed demand*
μ	*mean of normally distributed demand*
Q_s	*quantity that survives*
Q_d	*dispatched quantity that is ordered by the retailer*
Q_r	*quantity that will get spoiled if not rerouted*
P_r	*price charged by the retailer*
P_r'	*price salvaged for the deteriorating items*
τ	*freshness keeping effort*
ϕ	*degree of spoilage at destination*
θ	*degree of freshness at destination*
Q_s^*	*optimal quantity that retailer wants to survive to meet the demand*

4.2 Case 1: No IoT implementation and No freshness control

In this case, we have considered that the retailer is not willing to invest in IoT technologies. Furthermore, 3PL provider is not interested in freshness keeping effort. In the absence of IoT, there is no rerouting, and the entire quantity is delivered to the retailer's store irrespective of the quality. At the retailer's store, the quantity spoiled ($\frac{\phi Q_s}{(1-\phi)}$) are disposed-of at a cost S , rest $Q_s = (1-\phi)Q_d$ that survives is sold at a price P_r . Therefore, in a newsvendor setting, the retailer's profit is given by (4), supplier's profit is given by (5) and 3PL profit is given by (6):

$$\Pi_r = \int_0^{Q_s} \left(xU - (Q_s - x)O\right) f(x,\theta)dx + \int_{Q_s}^{\infty} Q_s U f(x,\theta)dx - \frac{(C_t + S + W)\phi Q_s}{(1-\phi)} \qquad (4)$$

$$\Pi_s = (W - C_s)Q_d \qquad (5)$$

$$\Pi_l = (C_t - c_t)Q_d \qquad (6)$$

A little consideration will show that the optimal order quantity for the retailer could be given by $Q_d^* = \frac{Q_s^*}{(1-\phi)}$, where,

$$F(Q_s^*) = \frac{U}{O+U} - \frac{(C_t + S + W)\phi}{(1-\phi)(O+U)}. \qquad (7)$$

4.3 Case 2: IoT without freshness control

With IoT implementation, the quantity that is getting spoiled gets rerouted; this quantity could be salvaged at a discounted price P_r' and is given by $Q_r = \frac{\phi Q_s}{(1-\phi)}$. However, there will be an additional cost for IoT implementation and extra rerouting cost charged by the 3PL provider. Freshness keeping effort remains zero. In this case, the retailer's profit will be given by:

$$\Pi_r = \int_0^{Q_s} \left(xU - (Q_s - x)O\right) f(x,\theta)dx + \int_{Q_s}^{\infty} Q_s U f(x,\theta)dx + \frac{(P_r' - W - C_t - C_r)\phi Q_s}{(1-\phi)} - Q_d C_{iot} \qquad (8)$$

3PL Profit:

$$\Pi_l = (C_t - c_t)Q_d + (C_r - c_r)Q_r \qquad (9)$$

It can be shown that the optimal order quantity for the retailer could be given by $Q_d^* = \frac{Q_s^*}{(1-\phi)}$, where,

$$F\left(Q_s^*\right) = \frac{U}{(O+U)} + \frac{\left(P_r' - W - C_t - C_r\right)\phi}{(O+U)(1-\phi)} - \frac{C_{iot}}{(1-\phi)(O+U)}. \tag{10}$$

4.4 Case 3: IoT with freshness control:

With freshness control, where τ is the freshness keeping effort, and the 3PL has to incur an additional cost of freshness control $c(\tau) = c_o \tau^k$. However, this will lead to an improvement in the degree of freshness at the point of delivery such that $\theta = 1 - \frac{\beta}{\alpha^\tau}$ and therefore there will be an increase in the mean of the normally distributed demand as $\mu = \gamma\theta$. Here, the retailer's profit remains the same as given in (8); however, 3PL Profit becomes:

$$\Pi_l = \left(C_t - c_t\right)Q_d + \left(C_r - c_r\right)Q_r - c_o \tau^k \tag{11}$$

Once again the supplier's profit formula remains the same. This case, however, has to be solved using Stackelberg game theoretic approach as both retailer's and 3PL provider's decision (order quantity Q_d^* and freshness keeping effort τ respectively) affects the profit functions of the other player.

4.5 Case 4: Coordination between retailer and 3PL provider:

When retailer and 3PL coordinates we have to combine both the profit functions of the retailer and the 3PL such that C_t and C_r are removed from the equations. Retailer's and 3PL provider's combined profit will be given by (12). Furthermore, the supplier's profit remains the same as given in (5).

$$\Pi_c = \int_0^{Q_s} \left(xU - \left(Q_s - x\right)O\right) f(x,\theta)dx + \int_{Q_s}^{\infty} Q_s U f(x,\theta)dx + \frac{\left(P_r' - W - c_t - c_r\right)\phi Q_s}{(1-\phi)} - \frac{Q_s C_{iot}}{(1-\phi)} - c_o \tau^k \tag{12}$$

In case 3, the problem becomes that of a Stackelberg game, where retailer and 3PL can alternatively be leader and follower. When the retailer is the leader, we found that profit function for 3PL, i.e. (11), is non-convex and therefore it is difficult to obtain a unique optimal response for 3PL. However, when 3PL is the leader, profit function for the retailer, i.e. (8), is concave and optimal response could be obtained for the retailer. However, when the retailer's response is feed into the 3PL's profit function, the objective function once again is non-convex. Similarly, for case 4 where retailer and 3PL coordinates, the objective function is found to be non-convex. To maximize the non-convex profit function obtained for case 3 and 4, we employed off the shelf optimization routine available in Mathematica that uses techniques like simulated annealing, gradient search, etc. to find global optimal.

5. NUMERICAL EXPERIMENT

In this section, results of numerical experiments are presented. Some useful insights are generated using data approximated from real word scenario, assuming P_r=75, P_r'=45, W=35, C_t=15, c_t=9, C_r=10, c_r=4.5, a=1.2, b=0.2, γ=120, β=0.3, α=1.3, σ=20, c_o=4.5, C_{iot}=2, and k=3.10. Optimal order quantity (Q_d^*), optimal freshness keeping effort and profits generated for the retailer and the 3PL are calculated and the results obtained for the four cases discussed in §4.2 to §4.5 are presented in the table below (table 1).

Table 1: Optimal values for Qs, t and respective profits

	Q_d^* in units	τ*	Retailer's Profit	3PL's Profit
Case 1: No IoT implementation	94	0	621	565
Case 2: IoT without freshness control	113	0	1347	677
Case 3: IoT with freshness control	121	1.15	1621	827
Case 4: 3PL & Retailer Coordinates	152	3.01	2725	

5.1 Discussion

Our results suggest that there can be a significant increase in retailer's profit when it incorporated IoT enabled rerouting even in the absence of freshness keeping effort (see case 1 and 2 in table 1). In other words, even if the 3PL provider is not willing to improve its freshness keeping effort, the implementation of IoT by retailer alone can improve the supply chain profits. The 3PL is also the one who gets benefited as its profit has increased from 565 to 677; therefore, the total supply chain profit increases by the help of IoT alone.

In case 3, when 3PL is willing to improve its freshness keeping effort, the order quantity further increases from 113 to 121. This is because, as the freshness keeping effort of 3PL provider increases, freshness level at the destination (retailer's store) increases resulting in a higher demand for the product. Overall supply chain profit increases further. In case 4, when retailer and 3PL are willing to coordinate, we observe a huge increase in the ordered quantity as well as total supply chain profit. Total supply chain profit increases from 2438 as in case 3 to 2725 in case 4.

5.2 Limitations

The analysis presented in this paper is based on data inspired from real-world situations, however, with real data collected for different types of fresh products, one can assess the actual level of freshness control and order quantities that will be optimal for the given cold chain.

Furthermore, initial investment needed to come up with IoT and freshness keeping infrastructure are not considered in this paper. However, knowing the initial investment and fixed operating cost, one can easily calculate the internal rate of returns using the net present value approach.

6. CONCLUSION

In this paper, we have developed formulations to assess the profits that the retailer, 3PL provider, and supplier could attain by implementing IoT and freshness control. It is assumed that the retailer is operating in a newsvendor setting where it faces stochastic demand, such that the wholesale and retail price of the product is fixed and determined by the market forces. This article deviates from the previous literature by analyzing the scope for implementation of package level IoT devices in long distance fresh food transportation.

The paper reflects that IoT can enable the retailer to determine whether the product is getting spoiled and if so, allowing them to reroute and salvage those packages to avoid losses. By doing so, the overall cold chain profit is found to have increased. Results further show that there are significant gains in cold chain profits when 3PL employs freshness control while transporting the product from source to destination. Profits attained by retailer, 3PL, and supplier could easily be calculated using our formulation. Cases as discussed in this paper can be used as a basis to design new contracts for coordination in the cold supply chain.

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